

Likewise in the case of the superior air, equations (10), (11), and (13) become, respectively,

$$(23) \quad G_a = \frac{T_a}{T} \left[\frac{g\alpha H_i}{lT_i} + G_o \right],$$

$$(24) \quad \frac{1}{l} \frac{\partial G_a}{\partial t} = \frac{g\alpha\beta}{l^2} \frac{10^5}{7.6} \left(\frac{2.273 - T_i}{T_i^3} \right) T_a + \frac{T_a}{lT_i} \left(\frac{\partial G_o}{\partial t} + \frac{\beta}{T_i} G_o \right),$$

$$(25) \quad I_2 = \frac{10^5 p_o e^{-\frac{H_i}{H}}}{7.6 \cdot 5.5 \frac{R}{m} l T_i} \left[1 - \left(\frac{T_a}{T_i} \right)^{5.5} \right] \left\{ \frac{10^5 g\alpha\beta (2.273 - T_i)}{7.6 l T_i} + T_i \frac{\partial G_o}{\partial t} + \beta G_o \right\} \text{ gm/cm/sec.}$$

To find the surface pressure distribution at time t , it is necessary to solve the following equation for p_o :

$$(14) \quad \frac{\partial p_o}{\partial t} = 0.98 \times 86400 \frac{\partial I}{\partial r},$$

where $I = I_1 + I_2$, and I_1, I_2 are given by equations (22) and (25).

As can be seen after writing G_o in terms of p_o , and performing the required differentiations, a partial, non-linear differential equation in p_o , with variable coefficients, results. The most practicable method of finding a solution appears to be by successive approximations. First, the pressure profile is computed when variations in p_o (or G_o) are neglected; this can be easily done as shown above. Then the surface geostrophic wind distribution (G_o) is found; and also, by numerical methods, the surface isallobaric velocity distribution $\left(\frac{1}{l} \frac{\partial G_o}{\partial t} \right)$. These latter two quantities are then substituted in equations (22) and (25), resulting in a second approximation for I_1 and I_2 . By numerical methods $\frac{\partial I_1}{\partial r}$ and $\frac{\partial I_2}{\partial r}$ are found, and therefore also the second approximation for $\frac{\partial p_o}{\partial t}$.

The process may then be repeated to give further approximations. However, because of the limitations in the numerical methods used, only the second approximation for the pressure tendency profile could be found with any assurance; this is shown in figure 7 as the dashed curve. As should be expected, the second approximation shows a smaller increase of pressure; the difference is especially marked at the center of the anticyclone, where the second approximation is about 24 percent smaller than the first, while at the periphery it is only 14 percent smaller. It has not yet been shown mathematically whether the successive approximations converge and, if so, whether the convergence is so rapid that the second solution is

sufficiently accurate. It does not seem worth while to spend more time on the mathematical problems involved, since, as pointed out above, the treatment here has neglected certain important dynamical considerations, such as conservation of angular momentum; this omission the author hopes to correct in a later paper.

CONSTANTS OF THE MODEL

26 days of cooling at a rate of 1.35° C./day;
Vertical growth of the polar continental air ~180 meters/day;
Horizontal growth of the polar continental air ~58 km/day;
Slope of the front ~1/300;
Inflow velocity of the superior air ~9 km/day;
Vertical ascent of the superior air ~30 meters/day;
Sinking of the front by contraction of the cooled air ~10 to 20 meters/day.

The superior air undergoes very little vertical displacement as it moves toward the center, since the ascent caused by motion up the frontal surface is almost compensated by the vertical contraction of the lower cooled air. At the same time, of course, the superior air is being transformed into polar continental air at a rate of 180 meters/day vertically; and, likewise, the discontinuity in inflow velocity is raised vertically at the same rate. The comparatively large inward velocities which existed in the superior air before it was transformed into polar continental air will no longer be maintained and will disappear by mixing with the slower moving air.

SUMMARY

When cooling of air occurs over a certain region, the air contracts, the isobaric surfaces are lowered, and a compensating inflow of air aloft raises the surface pressure and gives rise to a surface anticyclone. An explanation of the mechanics of the compensating inflow has been attempted on the basis of the Brunt-Douglas isallobaric velocity component, which is directed into the deepening cyclone aloft (polar cyclone). The vertical distribution of this inflow is studied; and it is found that in going through the front from the polar continental air to the air above, a many-fold increase in isallobaric velocity occurs, showing that almost all the increase in surface pressure results from convergence in the air above the lower cooled air.

At any given time in the life history of the growing polar anticyclone, it is possible to construct surface pressure tendency profiles, and the magnitude of the increases seems to be in satisfactory agreement with those observed on weather maps.

The next step in the problem is to include certain dynamical reasoning omitted in this preliminary treatment and then to explain the release of these large masses of cold air, which occurs in a discontinuous manner, sometimes with no apparent clue in the shapes of surface isobars or in 3- and 12-hour pressure changes.

METEOROLOGICAL ASPECTS OF HAILSTORMS IN NEBRASKA

By G. DAVID KOCH

[Department of Geography, University of Nebraska, Lincoln, Nebr.]

This paper presents the results obtained from an intensive study of the available data on hailstorms in Nebraska, which cover the 13-year period 1924-36, inclusive. These data from the files of the United States Weather Bureau office at Lincoln are the result of observations made by voluntary weather observers at cooperative Weather Bureau stations located in various parts of the State. The reports contain data pertaining to location, width, length, and direction of movement of the individual hailstorms. Each report was carefully checked by the offi-

cials of the Weather Bureau and thus obvious errors and superficial estimates were corrected. Few storms are recorded earlier than April or later than September. Even though hail should fall during the late fall and winter months a relatively small amount of damage is done to crops. Hence, only the months April to September, inclusive, are here considered.

Hail occurs only during the passage of a thunderstorm; and records indicate that destructive hail occurs in only a comparatively small number of thunderstorms. Of the

total of 13,996 thunderstorms reported for the 13-year period, only 940 or 6.1 percent were recorded as having been attended by moderately heavy hail. Considering only the 6 months of the year we find the percent of reported thunderstorms accompanied by hail was highest in April and May, and lowest in September.

TABLE 1.—*The total number and percent of thunderstorms attended by hail for the years 1924-36 inclusive*

[Source of data: United States Weather Bureau, Lincoln, Nebr.]

Month	Total number for 13-year period	Total number accompanied by hail	Percentage accompanied by hail
April.....	1,204	120	9.9
May.....	1,792	201	11.2
June.....	4,780	269	5.6
July.....	2,359	142	6.0
August.....	2,636	145	5.5
September.....	1,225	63	5.1
Total.....	13,996	940	6.1

More hailstorms were formed in frontal thunderstorms than in any other type. Fifty-four and a half percent of the hailstorms occurred in the frontal thunderstorms, 42.4 percent in the heat type, and only 3.1 percent in or near the center of an area of high pressure.

TABLE 2.—*The percent of thunderstorms attended by hail, in relation to the different types of pressure areas*

[Source of data: United States Weather Bureau, Lincoln, Nebr.]

Month	Percent in warm sector of low	Percent of frontal type	Percent in center of high
April.....	2.2	7.4	0.2
May.....	10.0	11.7	1.1
June.....	10.0	17.3	.5
July.....	7.0	5.1	.8
August.....	11.0	9.9	.5
September.....	2.2	3.1	.0
Total.....	42.4	54.5	3.1

The hours during which the largest number of hailstorms occurred show little relation to the hours of greatest precipitation. Sixty-one percent of the hailstorms took place between the hours of 2 p. m. and 7 p. m., and only 21 percent occurred between 8 p. m. and 6 a. m., whereas during the period 1905-23 at Lincoln, about 34 percent of the total amount of rain fell from 6 a. m. to 6 p. m. and

about 66 percent from 6 p. m. to 6 a. m.¹ It is generally accepted that the major portion of summertime rainfall comes as the result of thunderstorms. Kincer² found that in a small area centered roughly over eastern Nebraska, 65 percent of the summer rain falls between the hours of 8 p. m. and 8 a. m. With the exception of a small area in southern Arizona the area in Nebraska experienced the highest summer nighttime precipitation in the United States.

TABLE 3.—*The number and percent of hailstorms which occurred during the 24 hours of the day*

[Source of data: United States Weather Bureau, Lincoln, Nebr.]

Hour	Number	Percent	Hour	Number	Percent
6-10 a. m.....	9	2.3	5-6 p. m.....	44	11.3
10-12 noon.....	7	1.8	6-7 p. m.....	51	13.4
12-1 p. m.....	4	1.0	7-8 p. m.....	36	9.4
1-2 p. m.....	9	2.3	8-9 p. m.....	20	5.2
2-3 p. m.....	26	6.8	9-10 p. m.....	25	6.5
3-4 p. m.....	53	13.9	10-12 midnight.....	18	4.7
4-5 p. m.....	58	15.0	12-6 a. m.....	20	5.2

Whether more afternoon thunderstorms were actually attended by hail, or whether numerous nighttime hailstorms were not reported, must remain a matter of conjecture, however, until longer and more complete records are available.

Of the 404 hailstorms for which data are available, 78.8 percent came from some westerly direction. The largest number coming from any one direction was 173 or 42.8 percent, from the northwest. The smallest number, 5 or only 1.2 percent, was reported from the east.

TABLE 4.—*Direction of movement of hailstorms in Nebraska, 1923-36, inclusive*

[Source of data: United States Weather Bureau, Lincoln, Nebr.]

Directions from which hailstorms came	Number of storms	Percent of total number of storms	Directions from which hailstorms came	Number of storms	Percent of total number of storms
North.....	28	6.9	South.....	5	1.2
Northwest.....	173	42.8	Southeast.....	13	4.4
West.....	63	15.6	East.....	6	1.5
Southwest.....	82	20.4	Northeast.....	29	7.1

¹ Carter, Harry G. Variation in hourly rainfall at Lincoln, Nebr. MO. WEA. REV., April 1924, 52: 208-212.

² Kincer, Jos. B. Daytime and nighttime precipitation and their economic significance. MO. WEA. REV., Nov., 1916, 44: 623-633.

THUNDERSTORM FREQUENCIES FOR 6-HOUR PERIODS AT MILES CITY, MONT.

By LOUIS R. JURWITZ

[Weather Bureau, Miles City, Mont., January 1937]

Miles City is about 200 miles east-northeast of the Continental Divide which runs through northwestern Wyoming. The city is on the Yellowstone River, approximately 150 miles from where it enters the Missouri River, and at the junction of the Tongue and the Yellowstone Rivers. The elevation of the Weather Bureau station at Miles City is 2,351 feet. The surrounding region to the north and west is flat with low, rolling swells; to the east, south, and southwest the country is more rugged with hills rising to an elevation of 500 to 800 feet above the valley floor.

Vegetation is sparse except on the hills to the east which are moderately covered with scattered stands of pine. The hills to the south and southwest are bare and of a "badland" character favoring convectional thunderstorms. Fully 75 percent of the thunderstorms which occur at the station have their origin to the south and southwest while the remainder of the convectional type storms move into the valley from the hills that lie to the east.

Thunderstorms are in general of moderate intensity, and as a rule last from 2 to 6 hours, with occasional excessive precipitation and moderate hail.